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Update on Risk Reduction Activities for a Liquid Advanced Booster for NASA's Space Launch System

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Overview and Introduction to ABEDRR

- **Goals of NASA's Advanced Booster Engineering Demonstration and/or Risk Reduction (ABEDRR) are to:**
  - Reduce risks leading to an affordable Advanced Booster that meets the evolved capabilities of SLS
  - Enable competition by mitigating targeted Advanced Booster risks to enhance SLS affordability
- **SLS Block 1 vehicle is being designed to carry 70 mT to LEO**
  - Uses two five-segment solid rocket boosters (SRBs) similar to the boosters that helped power the space shuttle to orbit
- **Evolved 130 mT payload class rocket requires an advanced booster with more thrust than any existing U.S. liquid- or solid-fueled boosters**

Scope of This Presentation

- **In October 2012 and February 2013, NASA awarded a contract to Dynetics, Inc. (with Aerojet Rocketdyne as a major subcontractor):**
  - To demo the use of modern manufacturing techniques to produce and test several primary components of the F-1 rocket engine originally developed for the Apollo Program, including an integrated powerpack
  - To demo innovative fab techniques for metallic cryo tanks
- **Early 2014, NASA and Dynetics agreed to move additional large liquid oxygen/kerosene engine work under Dynetics**
  - Originally had been its own ABEDRR prime contract to Aerojet
- **Led by Aerojet Rocketdyne, work is focused on an Oxidizer-Rich Staged Combustion (ORSC) cycle engine**
  - Can apply to both NASA's Advanced Booster and other launch vehicle applications, including Atlas V booster engine
  - Effort will demonstrate combustion stability and performance of a full-scale ORSC cycle main injector and chamber
- **This presentation will discuss the Dynetics ABEDRR engine task (both efforts) and structures task achievements to date**

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Dynetics Risk Reduction Task Summary

A

B

A

Engineering Demonstrations and Risk Reduction Tasks	*Benefit of Proposed Effort/Status at Start of DDT&E*
F-1B Engine Risk Reduction	
Aerojet Rocketdyne Lead	
• Gas Generator Build and Test	• Full-Scale, Low-Cost, Production-Like, Throttling GG Hot-Fired
• Turbopump Build	• Full-Scale, Low-Cost, Production-Like, Throttling TPA Built
• Powerpack Build and Test	• Full-Scale, Low-Cost, Production-Like, Throttling PPA Hot-Fired
• Thrust Chamber Assembly Design and Build	• Full-Scale, Low-Cost, Production-Like, HIP-Bonded TCA Demonstrated
Structures Risk Reduction	
Dynetics Lead	
• Cryotank Assembly Build	• Full-Scale 18-ft Diameter Flight-Like Tank and Intertank Verified
• Cryotank Proof and Thermal Cycle	• Full-Scale Design, Tooling, and Build Processes Verified
ORSC Cycle Engine Risk Reduction	
Aerojet Rocketdyne Lead	
• Main Injector and Thrust Chamber Assembly Design, Build, and Test	• Full-Scale Demonstration of Combustion Stability and Performance Measurement

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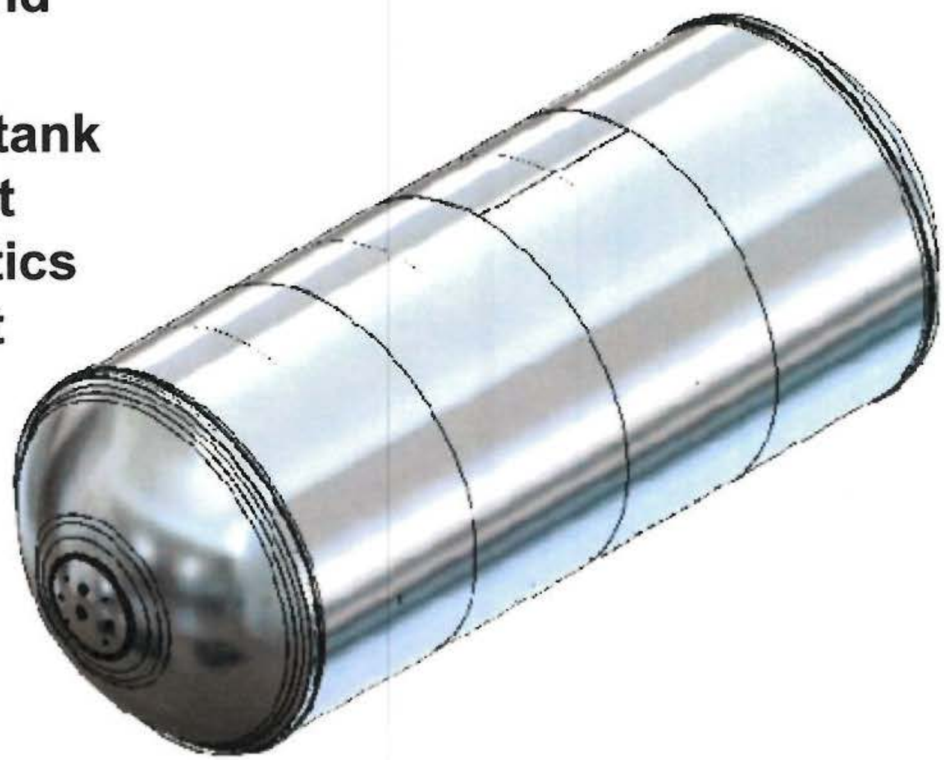
Overall F-1B Engine Risk Reduction Summary

- **Program objective was to reduce F-1B engine development risks—despite funding challenges, the effort met this objective:**
  - Demonstrated F-1B engine and component understanding and readiness
  - Completed a heritage gas generator (GG) hot-fire test series, proving throttling capability
  - Completed an additively manufactured GG inejctor hot-fire test series, proving similarity to heritage
  - Disassembled and reverse engineered existing Mk-10A turbopump
  - Demonstrated long-term affordability through full-scale demonstrations of an additively manufactured GG injector and a cast LOX volute, turbine blades, and turbine manifold
  - Prepared main propellant valves for test
  - Integrated engine loads and design, developed transient operational models, and designed interfaces with the facility for Powerpack testing
  - Developed a new MCC design focused on dramatic cost reductions

Structures Risk Reduction – Cryotank Build

- Structures risk reduction task planned to validate the designs, materials, equipment, and processes to produce robust and affordable structures
- The task created a full-scale cryotank assembly that was verified by proof pressure and cryo-thermal cycle testing
- Original plan was to build a tank with four barrel sections, but NASA negotiated with Dynetics to reduce schedule and cost by building a tank with a single cylindrical barrel
  - Circumferential welding still demonstrated, and testing still completed



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Structures Risk Reduction – Testing

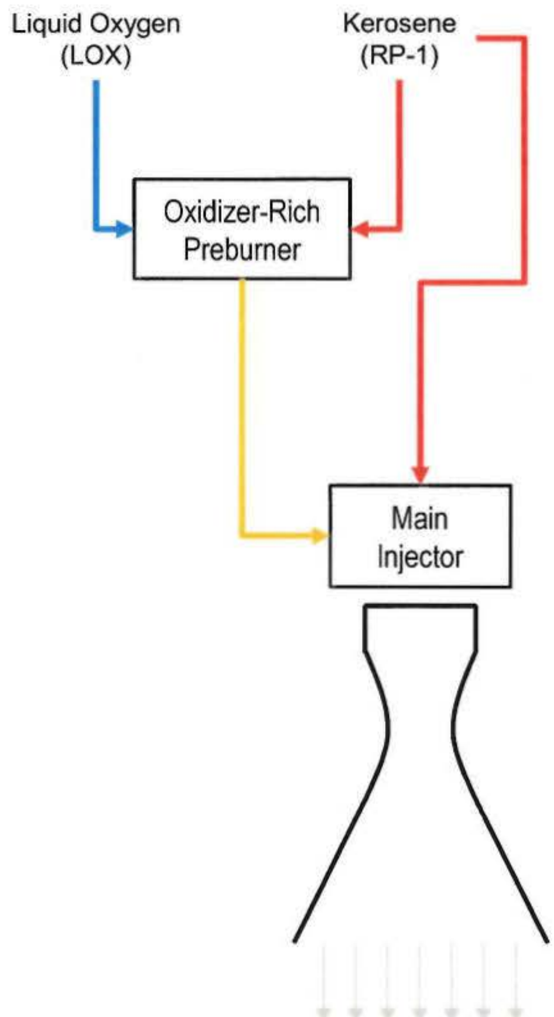
Cryothermal Cycle / Proof Test

Integrated test article chilled with LN_2

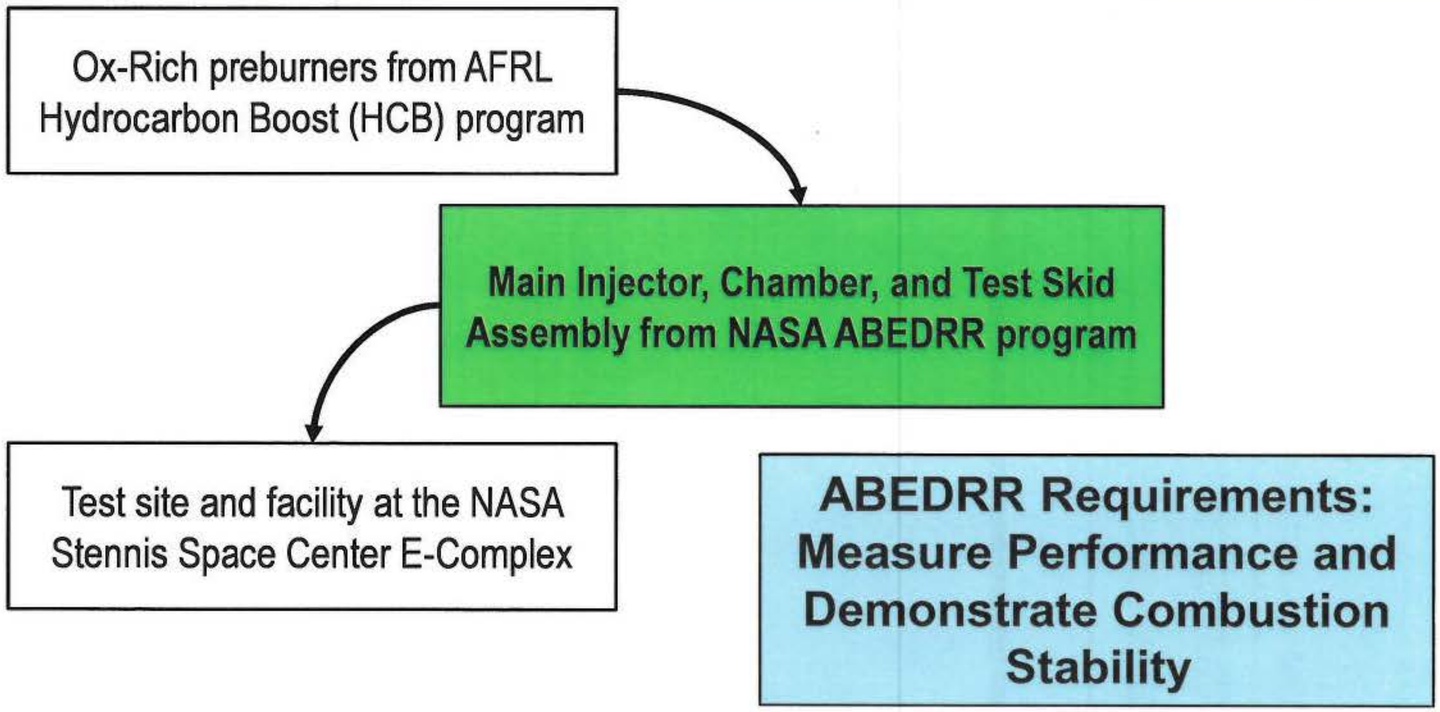
Burst Test

Moments after tank burst

Ox-Rich Staged Combustion (ORSC) Cycle Engine



NASA/USAF-Funded Integrated Ox-Rich Test Article



- Preburner testing at the 250 klbf thrust level. ORSC main injector combustion stability and injector performance results at 500 klbf thrust level. Direct design information and model validation data.

= Focus of this presentation

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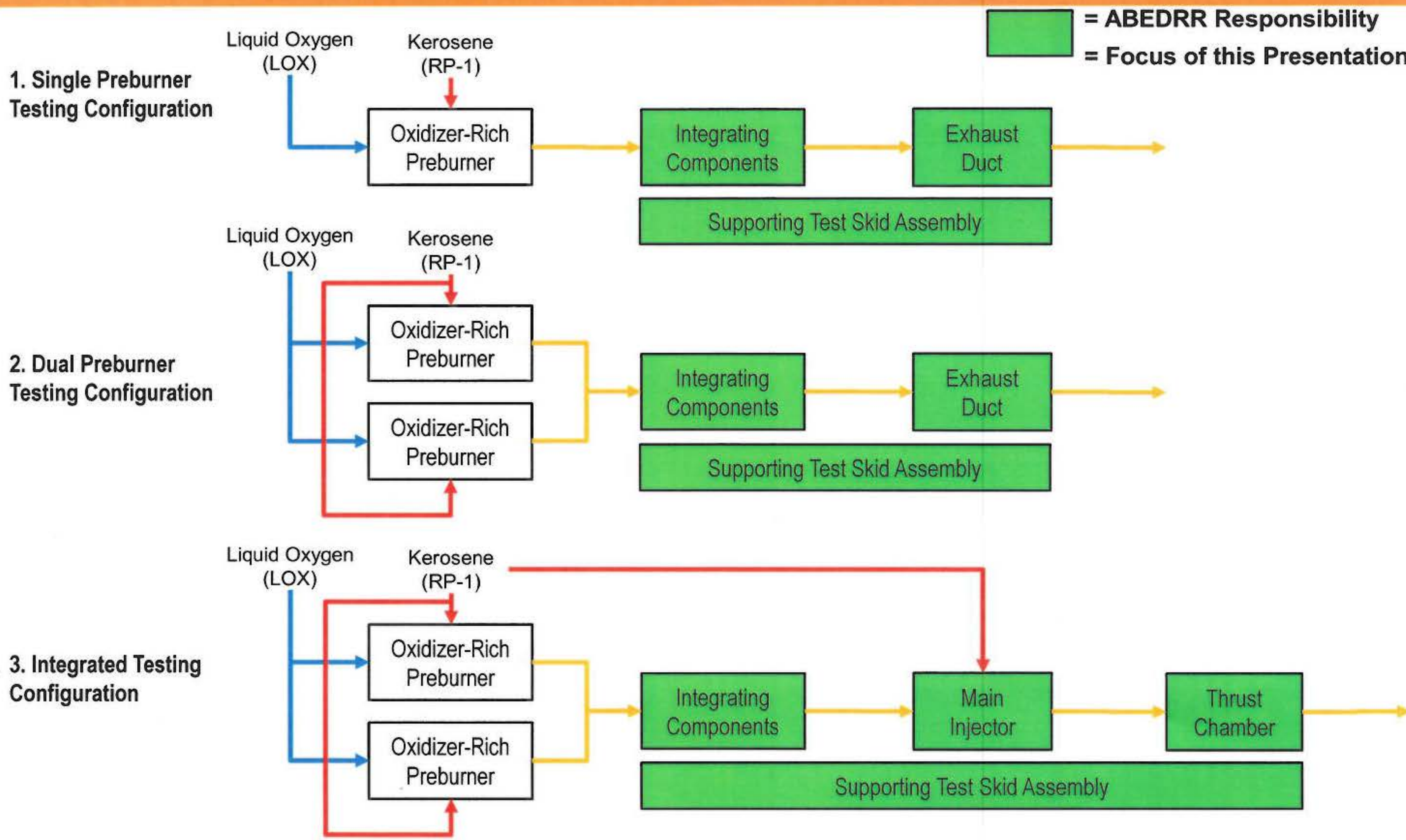
Test Configurations



Integrating Components (IC) Summary Status

- **Accomplishments**
  - Completed IC CDR in Aug 2015
  - Completed IC Delta CDR in Nov 2015
  - Completed pouring of all cast parts
  - Completed casting process on several key components
- **Status**
  - Drawing status: 74% released
  - All remaining major component machine drawings are in signature cycle
  - Machining of IC hardware on schedule to support testing
- **Upcoming Events**
  - Release remaining IC piece part drawings
  - Complete machining of IC hardware per schedule

Main Injector Summary Status

- **Accomplishments**
  - Completed CDR in Mar 2016
  - Completed Delta CDR in June 2016
  - Ran hydraulic CFD to design flow distribution through manifold and injector elements
  - Ran reacting-flow CFD in sub-models and full-sector models to determine driving temperatures at various power levels, engine conditions, cooling flows, etc.
  - Resolved thermal compatibility issues to eliminate hot spots / streaks
  - Performed acoustic analyses to find stable configurations and conditions
  - Performed structural analysis to determine injector has positive margins and meets life requirements
  - Finalized design of injector elements and injector assembly
    - Included stability aids (baffles and cavities) for improved high frequency stability margin
  - Developed fabrication plan, and verified / updated with sub-scale injector Manufacturing Technology Demonstrators (MTDs)

Main Injector Summary Status (cont'd)

- **Status**
  - Completing cold flows to determine final propellant flow paths
  - ~80% of drawings released and out for procurement
  - Completed major injector forgings; moved to machining
  - Majority of injector components in fabrication

Chamber Summary Status

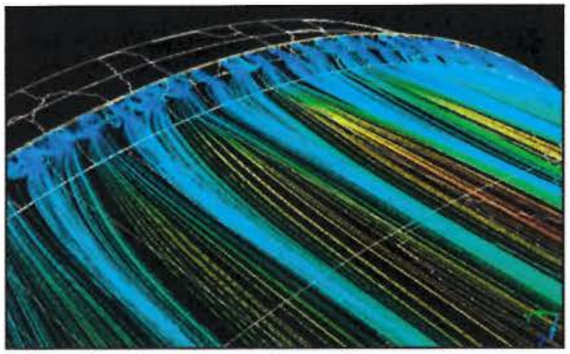
- **Accomplishments**
  - Ran reacting-flow CFD in sub-models and full-sector models and thermal analysis to determine driving temperatures at various power levels, engine conditions, cooling flows, etc.
  - Resolved thermal compatibility issues to eliminate hot spots / streaks
  - Performed structural analysis to determine chamber has positive margins and meets life requirements
  - Finalized cooling design with thermal/structural and flow requirements
  - Finalized design of chamber
    - **Finalized cooling approach**
    - **Modified features to reduce strain and improve low cycle fatigue**
  - Optimized geometry for manufacturability
  - Baselined braze parameters; demonstrated braze parameters
  - Defined and matured manufacturing processes

Chamber Summary Status (cont'd)

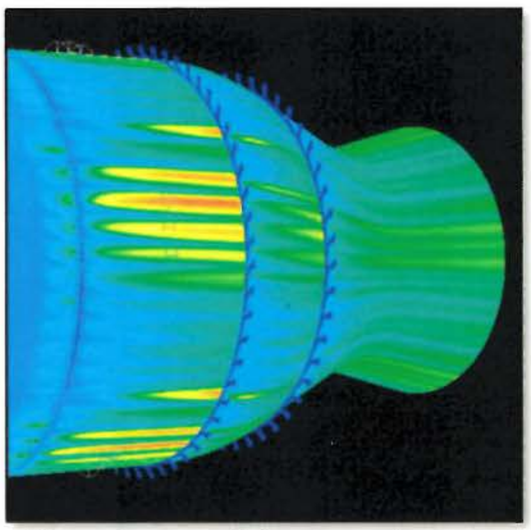
- **Status**
  - Drawings ~70% complete
  - Procurement on schedule
  - Machining of hardware on schedule to support testing

- **Upcoming Events**
  - Complete remaining braze trials
  - Release remaining piece part drawings
  - Complete machining of hardware per schedule

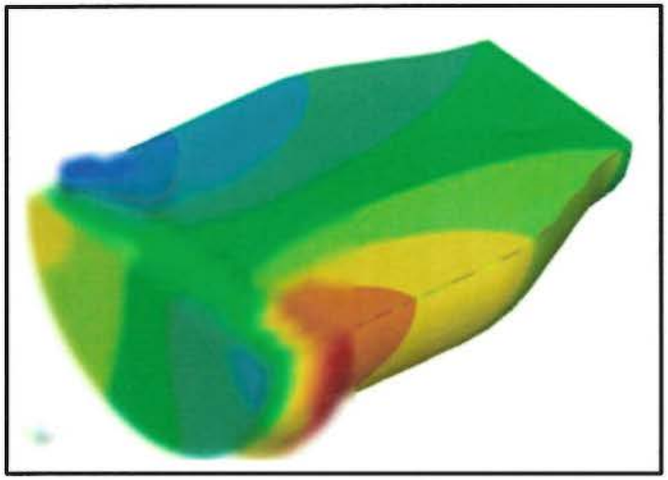
Examples of Fluid, Thermal, Structural, and Acoustic Analyses



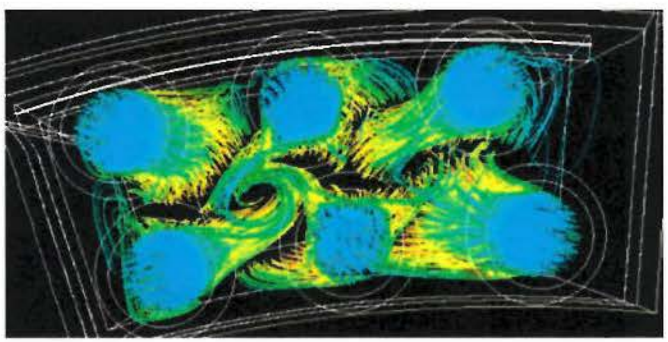
Analysis of coolant flow along chamber wall



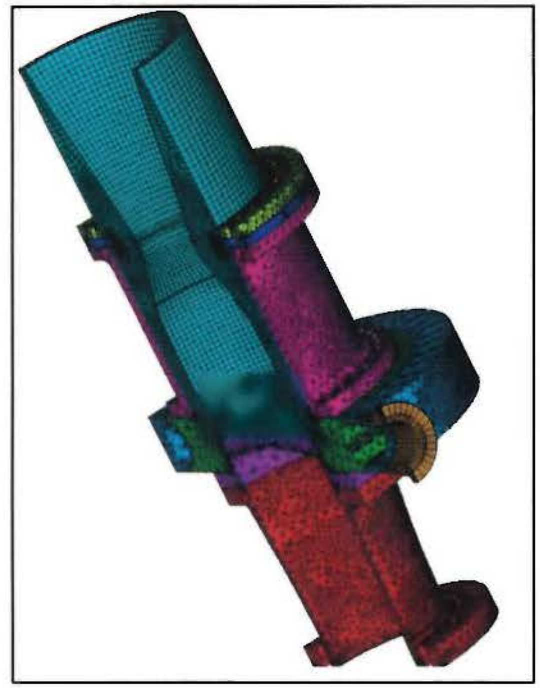
Chamber wall temperature analyses using CFD



Stability analysis / acoustic modeling of injector and chamber



Reacting flow CFD of injector streamlines



Structural model of thrust chamber assembly

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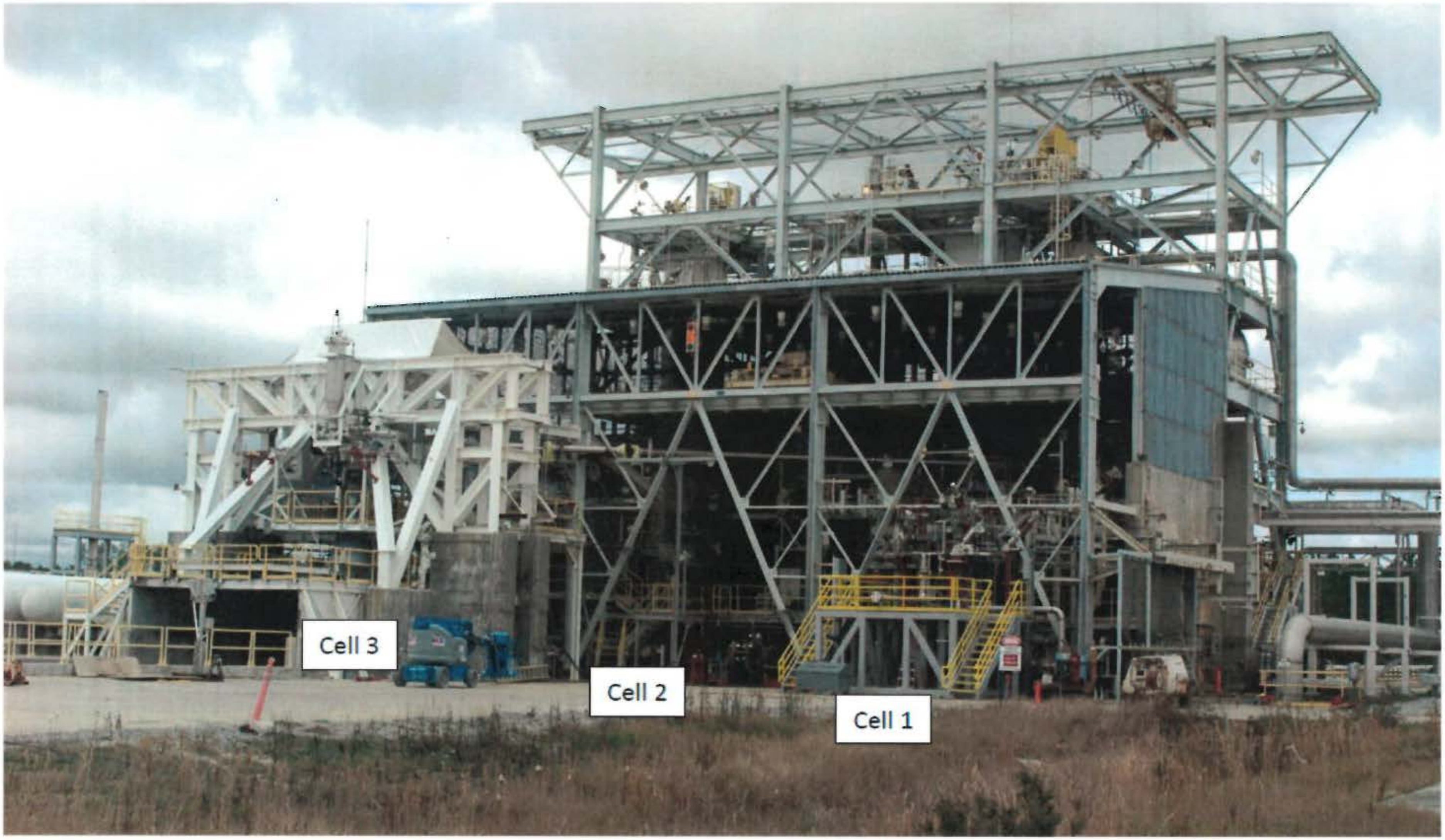
Testing at NASA Stennis Space Center Stand E1



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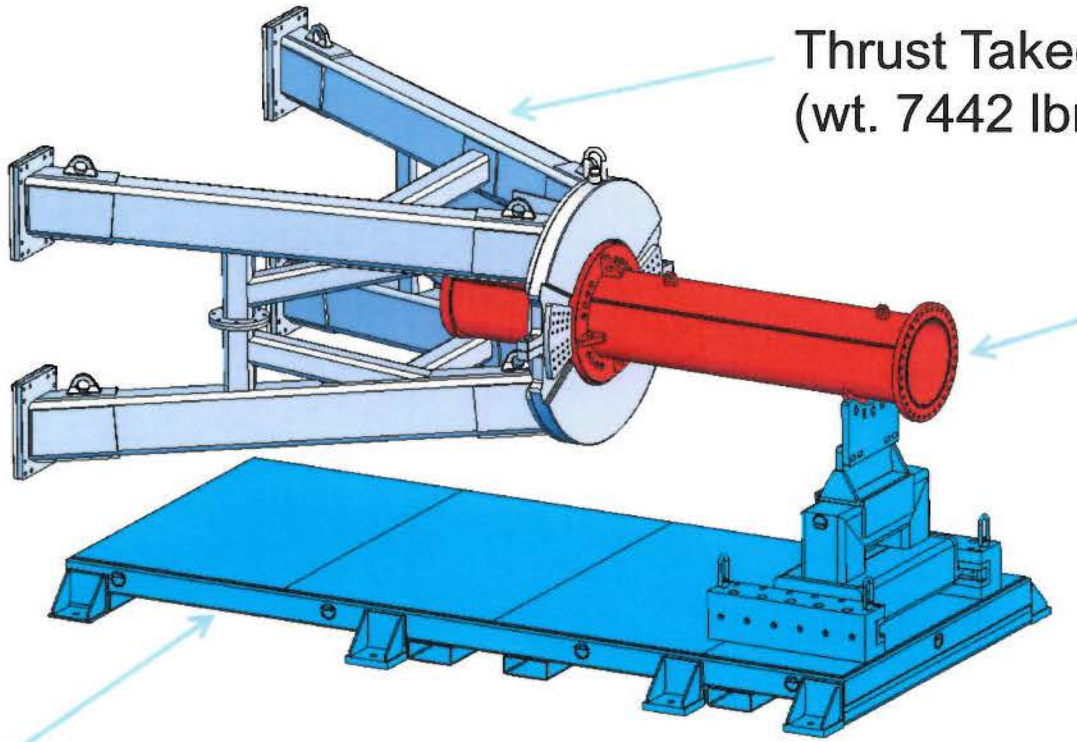
Test Skid Assembly Design Status

- **Completed Conceptual Design Review in Oct 2015**
- **Completed Preliminary Design Review in Dec 2015**
- **Completed Detailed Design Review in Feb 2016**



Test Skid Assembly Build Status

- **Thrust Takeout Structure**
  - Final welding complete; post-weld inspection complete
  - Thrust takeout plates in machining
  - Stress relief after welding
  - Then final machining and painting
- **Exhaust duct**
  - Final welding complete; post-weld inspection complete
  - Moved to large gantry mill for post-weld machining
  - Then proof testing and final processing
- **Carriage assembly**
  - Final weld complete; post-weld machining complete; inspection complete
  - Next step: painting
- **Platform**
  - Welding in work; will finish sometime next week
  - Next steps: NDT → paint
- **Build completion expected end of October**

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Test Skid Assembly Build Progress
Thrust Takeout Structure (Post-Weld)

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Test Skid Assembly Build Progress (cont'd)
Exhaust Duct (Post-Weld)

Test Skid Assembly Build Progress (cont'd)
Carriage Assembly (Post-Weld)

Summary

- Dynetics has designed innovative structure assemblies; manufactured them using FSW to leverage NASA investments in tools, facilities, and processes; conducted proof and burst testing, demonstrating viability of design/build processes
- Dynetics/AR has applied state-of-the-art manufacturing and processing techniques to the heritage F-1, reducing risk for engine development
- Dynetics/AR has also made progress on technology demonstrations for ORSC cycle engine, which offers affordability and performance for both NASA and other launch vehicles
    - Full-scale integrated oxidizer-rich test article
    - Testing will evaluate performance and combustion stability characteristics
    - Contributes to technology maturation for ox-rich staged combustion engines